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An integrated approach for a sustainable supplier selection based on Industry 4.0 concept

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Abstract
The recent advances in sustainable supply chain management are integrated with Industry 4.0 concepts. This study develops a new integrated model to consider the sustainability and Industry 4.0 criteria for the supplier selection management. The proposed approach consists of the fuzzy best worst method (FBWM) and the two-stage fuzzy inference system (FIS) to assess the selection of suppliers. Firstly, this study determines a comprehensive list of Industry 4.0 and sustainability criteria along with their definitions. Then, the importance weight of each criterion is computed by the FBWM. Subsequently, a two-stage FIS is devoted to nominate the suppliers' performance with regard to the sustainability and Industry 4.0 criteria. To show the applicability of our integrated model, a case study for a textile company in Iran is provided. Finally, some sensitivity analyses are done to assess the efficiency of the proposed integrated approach. One finding is to establish a decision-making framework to evaluate suppliers separately, rather than relatively in a fuzzy environment using Industry 4.0 and sustainability criteria.

Keywords Industry 4.0 · Sustainable supply chain management · Sustainable supplier selection · Fuzzy best worst method · Fuzzy inference system

Introduction

Sustainability is regarded as the most essential concept among supply chain managers to develop a sustainable system based on the economic, environmental, and social criteria for improving the general performance of organizations (Yazdani et al., 2021a, 2021b). In other words, in addition to the importance of economic criteria for any manufacturing company (Fallahpour et al. 2021), managers try to meet environmental and social requirements with regard to public opinions and government regulations (Dogan and Seker 2016; Dogan and Turkekul 2016; Dogan and Inglesi-Lotz 2017; Abdel-Baset et al. 2019). In this regard, simultaneous consideration of economic, environmental, and social criteria creates the triple bottom line concept and the implementation of this concept in the supply chain and business

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networks and develops the theory of the sustainable supply chain management (SSCM) (Mojtahedi et al., 2021).

The definition of the SSCM theory to design the supply chain network and coordination is an introduction to develop decision-making models and algorithms in this research area (Fathollahi-Fard et al. 2020a, 2020b). Majority of studies in the area of SSCM focused on the achievement of environmental sustainability as around 80% of greenhouse gas emissions are mainly generated by the suppliers in a supply chain network (Kuo et al. 2015; Tidy et al. 2016; Tseng et al. 2019; Pasha et al., 2021). Suppliers are the first echelon in the supply chain (Guarnieri and Trojan 2019), and they strongly affect a company's performance in terms of sustainability (Bai et al. 2019; Rashidi and Cullinane 2019; Liu et al. 2020). Thus, organizations need to assess their suppliers for long-term partnership (Nezhadroshan et al. 2020). Determining the suitable suppliers based on the sustainability is one of the most essential strategies for SSCM (Fallahpour et al. 2016; Kusi-Sarpong et al. 2019b). Choosing the appropriate suppliers helps managers to obtain the suitable raw materials at the right time, quantity, and quality (Kusi-Sarpong et al. 2019a; Tavana et al. 2021; Wang et al. 2021). It can be said that sustainable supplier evaluation and selection is a key activity that affects SSCM in various industries (Shahmansouri et al., 2021).

Although the sustainable supplier selection is widely studied, recent studies are exploring the impact of advanced technology and industrial informatics like Industry 4.0 on the supply chain's performance (Moosavi et al., 2021) and healthcare informatics (Fathollahi-Fard et al., 2021b). The Industry 4.0 concept strongly influences information sharing, knowledge transfer, and communication among different echelons of a supply chain (Gromoff et al. 2012; Kazantsev et al. 2018; Fathollahi-Fard et al. 2019; Kusi-Sarpong et al. 2019a; Zhang et al. 2020). For example, Gottge and Menzel (2017) pointed out that Industry 4.0 factors have been applied in more than one quarter of the German industries. Moreover, Glock and Hochrein (2011) concluded that by considering Industry 4.0 based factors, communication, transparency, and data availability are improved. Kusi-Sarpong et al. (2019a, 2019b) stated that advanced technology improves all the major functions from upstream to downstream of a sustainable supply chain.

Using Industry 4.0 concept is useful to rearrange delivery dates of products for the suppliers (Müller et al. 2017) and capability to customize products and traceability (Weyer et al. 2015). Prajogo and Olhager (2012) mentioned that the recent advanced technology and Internet of things, known as Industry 4.0, aid decision-makers to have a resilient supply chain for reducing the influence of internal and external disruptions using data analytics. Lee et al. (2015) stated that Industry 4.0 has a high impact to reduce the inventory level and to increase customer service performance. Kusi-Sarpong et al. (2019a, 2019b) indicated that Industry 4.0 is an appropriate concept for managing a supply chain, as it includes four principles known as interconnection, real-time information transparency, decentralization, and technical assistance. Therefore, the SSCM may be reformulated by Industry 4.0 to develop an integrated decision-making framework (Kusi-Sarpong et al. 2019a).

In recent years, although several studies have been accomplished to design a supply chain based on Industry 4.0, it is found that less attention has been devoted to develop a model that considers Industry 4.0 attributes in the context of sustainable supplier selection (SSS). It is seen that the incorporation of Industry 4.0 based criteria with conventional sustainability attributes has been less addressed for evaluating sustainable suppliers' performance. In addition, the majority of the SSS models are considered relative performance evaluation methods such as Analytic Network Process (ANP), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Data Envelopment Analysis (DEA), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and *Analytic Hierarchy Process (*AHP), even under a fuzzy environment (Jain et al. 2020). Such methods are unable to assess suppliers' performance one by one. One main disadvantage is that a complete data set of all the suppliers under evaluation is needed. It means that without a decision matrix that includes information about all the attributes of all the suppliers, these techniques cannot compute the suppliers' performance. Therefore, this study is aimed at integrating Industry 4.0 attributes with sustainability criteria to improve the comprehensiveness of SSS to reformulate the SSCM concept. Furthermore, it aims to fill the gap in the literature by developing new hybridized decision-making model comprising the fuzzy best worst method (FBWM) and two-stage fuzzy inference system (FIS) to enable decision-makers to evaluate suppliers' performance separately. The applicability of the proposed approach revealed in the textile industry in Iran (as one of the largest industries in Iran and one of the oldest in Middle East) has been selected as the case study. With regard to these contributions, this study aims to address following research questions:

- What is the concept of Industry 4.0 in the textile industry?
- How to integrate Industry 4.0 with sustainability criteria for evaluation of sustainable suppliers?
- How to develop an integrated FBWM with the two-stage FIS model to assess and select sustainable suppliers?

  All in all, this study makes the following highlights to the state of the art:

- Easing the understanding of the Industry 4.0 concept in the textile industry

- Integrating Industry 4.0 attributes with sustainability criteria for the SSS model
- Developing an integrated approach combining FBWM with the two-stage FIS model for the first time

Other parts of this paper are summarized as follows: the “Literature review” section collects the most relevant criteria and reviews the relevant studies with analyzing the research gaps. The developed integrated approach is described in the “Proposed approach” section. In the “Case study” section, the application of this paper in the textile industry is illustrated. Validation of the model is shown in the “Validation of the proposed approach” section. In the “Findings and Discussion” section, findings and discussion for managerial implications are given. Finally, a summary of this research with limitations and recommendations for future researches is presented in the “Conclusions and future works” section.

Literature review

The research on the SSCM is highly active, and many studies try to improve the efficiency of the supplier selection and network design in recent years (for example, see De and Mahata (2020, 2021); Bhattacharya and De (2021)(2021; Bhattacharya et al. (2021); De (2021)). Here, we firstly define the sustainability and Industry 4.0 criteria and then review the relevant models. Finally, the research gaps are identified to show that how our contributions can fill them.

Sustainability and Industry 4.0 criteria

Having the concept of triple bottom line (TBL), the supply chain and production systems are redefined (Fathollahi-Fard et al., 2021a). This concept consists of three dimensions which are economy, environment, and society (Ghadami et al., 2021). Hence, a sustainable system must pay attention to environmental and social factors, in addition to economic factors.

Having an evaluation of the performance of SSS, two issues must be considered (Fallahpour et al. 2017, 2021): (i) evaluative criteria and (ii) evaluation models. In other words, performance evaluation is an activity that uses a model to assess some alternatives based on several evaluative criteria. It goes without saying that the relevant literature provided different criteria or attributes to cover the concept of sustainability in the process of supplier selection. Fallahpour et al. (2017) highlighted 13 main sustainability criteria and 46 sub-criteria. They proved that the economic dimension is the most significant one among the sustainability pillars. In addition, they showed that among the sub-criteria, material cost has the highest weight in assessing suppliers’ sustainability performance. Mohammed et al. (2019) applied 10 sustainability criteria for the evaluation of SSS. Similar to Fallahpour et al. (2017), they stated that the economic dimension is the most essential aspect in the TBL. Most importantly, the cost is the main attribute for performance evaluation. In another study, Abdel-Baset et al. (2019) also reported the same results. Literally, it is revealed that economy is the main issue in SSS, and its corresponding criteria such as cost and quality are the salient attributes for performance assessment. Based on previous studies, the frequently used sustainability criteria for SSS are summarized in Table 1.

As can be seen, there are numerous sustainability indicators for SSS. However, the literature shows that there are only two previous studies (Ghadimi et al. 2019; Fallahpour et al., 2021) which have examined the concept of advanced technologies and industrial informatics like Industry 4.0 within the context of SSS. In addition to the criteria given in Table 1, this study assesses some criteria linked with Industry 4.0 including “Proper information technology (IT) to support Industry 4.0 technologies,” “availability and proficiency in collecting the data based on the environmental Internet of things (IoT),” and “adopting Industry 4.0 and circular economy for supply chain contributors.” However, existing attributes such as quality, price, and environmental performance evaluation are essential for SSS (Fallahpour et al. 2017; Mohammed et al. 2019). Thus, this paper aims to use both conventional sustainability and Industry 4.0 criteria.

Relevant studies

Since SSS is a multi-criteria decision-making (MCDM) process (Fallahpour et al. 2016; Krishankumar et al. 2017), the literature shows that different evaluation models or methods such as TOPSIS, AHP, ANP, and DEA have been applied. Here, we focus on recently published papers during the last decade. For example, Dobos and Vörösmarty (2014) used DEA with common weights analysis to measure the efficiencies of suppliers based on the percentage of reusability, CO_2emission, lead time, quality, and price. In another research, Fallahpour et al. (2016) firstly utilized DEA to compute the efficiencies of suppliers in the textile industry. Then, a mathematical model was generated using genetic programming (GP) to forecast their efficiencies. Fallahpour et al. (2017) integrated fuzzy preference programming (FPP) with fuzzy TOPSIS to evaluate suppliers based on sustainability attributes in the textile industry. Specifically, the weight of each criterion was determined using FPP, and the best supplier was selected by applying fuzzy TOPSIS. Guarnieri and Trojan (2019) proposed a supplier selection model that considers social, ethical, and environmental attributes in the textile industry. The model consists of three phases: (i) defining the criteria, (ii) computing the weights

Table 1 Frequently criteria for evaluation of SSS

Criteria or attributes	Researchers
Cost (price)	Fallahpour et al. (2016, 2017); Rashidi and Cullinane (2019)
Quality	Amindoust and Saghafinia (2017); Fallahpour et al. (2017); Rashidi and Cullinane (2019)
Delivery	Fallahpour et al. (2017); Mohammed et al. (2019); Rashidi and Cullinane (2019)
Financial capability	Amindoust et al. (2012); Zhou et al. (2016)
Innovativeness	Bai et al. (2010); Neumüller et al. (2016)
Flexibility	Büyüközkan and Çifçi (2011); Chaharsooghi and Ashrafi (2014); Fallahpour et al. (2017)
Service	Amindoust et al. (2012); Fallahpour et al. (2016, 2017)
Relationship	Bai and Sarkis (2010); Amindoust et al. (2012); Orji and Wei (2014)
Technology	Bai and Sarkis (2010); Bai et al. (2010); Zhou et al. (2016)
Lead time	Govindan et al. (2013); Kannan et al. (2015)
Environmental management system	Amindoust et al. (2012); Azadi et al. (2015); Fallahpour et al. (2017)
Energy and resource consumption	Bai and Sarkis (2010); Bai et al. (2010); Amindoust et al. (2012)
Greenhouse gas emission	Chaharsooghi and Ashrafi (2014); Kannan et al. (2015)
Pollution control	Bai and Sarkis (2010); Bai et al. (2010); Amindoust et al. (2012)
Reuse	Amindoust et al. (2012); Fallahpour et al. (2017)
Green image	Girubha et al. (2016); Fallahpour et al. (2017)
Local communities influence	Bai and Sarkis (2010); Bai et al. (2010)
The interests and rights of employees	Amindoust et al. (2012); Chaharsooghi and Ashrafi (2014); Fallahpour et al. (2017)
Stakeholder engagement	Bai and Sarkis (2010); Bai et al. (2010); Sarkis et al. (2012)
Economic welfare and growth	Bai and Sarkis (2010); Bai et al. (2010); Govindan et al. (2013)
Social responsibility	Büyüközkan and Çifçi (2011); Kuo et al. (2011); Aktin and Gergin (2016)
Job safety and labor health	Amindoust et al. (2012); Sarkis et al. (2012); Fallahpour et al. (2017)
Job opportunity	Bai and Sarkis (2010); Bai et al. (2010); Sarkis et al. (2012); Fallahpour et al. (2021)

of the criteria using AHP, and (iii) applying elimination and choice translating reality (ELECTRE) for ranking and classifying suppliers. In a different paper, Safaeian et al. (2019) proposed a multi-objective decision-making model for the assessment of suppliers and order allocation based on the criteria of products' price, quality, cost, and environmental emissions in a fuzzy environment. Paunović et al. (2019) developed an assessment method for the supplier pre-qualification, supplier selection with regard to the sustainability criteria. In this field and the healthcare industry, Stević et al. (2020) proposed a heuristic MCDM for the SSS in Bosnia and Herzegovina. The benefits of this technique include considering an anti-ideal and ideal solution at the starting point of forming an initial matrix, closer determining the utility degree regarding both solutions, proposing a new method to specify utility functions and their aggregation, and the possibility for considering a large set of criteria and alternatives accompanied with the stability of the method. Additionally, Jain and Singh (2020) developed a two-phase FIS model based on the fuzzy Kano technique for the SSS in the application of iron and steel industry.

In a different model, Jain et al. (2020) integrated FIS and a heuristic fuzzy decision-making method to choose the most sustainable supplier. They applied their method to iron and steel industry in India. As such, a novel hybrid method combining the hierarchical fuzzy index based on the FBWM was proposed by Hendiani et al. (2020) to assess the SSS. Pérez-Velázquez et al. (2020) proposed an integrated FIS based on the VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) for the SSS and approved the applicability of their research in Photovoltaic Module Installation. Moreover, Hoseini et al. (2021) integrated fuzzy best worst method (FBWM) and fuzzy inference system (FIS) techniques for the SSS in the construction industry. They computed the final criterion weight by the FBWM approach, and the most sustainable supplier is chosen using the weighted FIS in terms of aspect and criterion level.

Furthermore, Amiri et al. (2021) applied FBWM using α-cut analysis for ranking the performance of sustainable suppliers. In their evaluation, the high "α" value and low "α" value represent low uncertainty and high uncertainty in the process of decision-making, respectively. Fallahpour et al. (2021) proposed a combination of fuzzy DEMATEL, fuzzy ANP, and FIS for evaluation of sustainability and resiliency criteria for the SSS. At last but not least, Zhang et al. (2021) integrated the rough DEMATEL and the fuzzy VIKOR (FVIKOR) methods to select the most sustainable supplier regarding the correlation between the evaluative criteria and the ambiguity of the criteria values. In their study, the rough DEMATEL method is employed to specify the weight of evaluative criteria which are interrelated or even conflicting, as well as the fuzzy VIKOR method is aimed to specify supplier rankings by transforming the fuzzy linguistic terms into precise data. Finally, the most relevant papers among reviewed papers are selected and summarized in Table 2.

Although many studies as given in Table 2 focused on the assessment of SSS, a few studies contributed to the Industry 4.0 in the context of supply chain management. For example, Schlüter and Hetterscheid (2017) presented the relevant technologies related to Industry 4.0 for supply chain processes. Oks et al. (2018) determined various opportunity fields for implementing industrial cyber physical systems in a supply chain. Hofmann and Rüsch (2017) explored the possible effects and future prospects of Industry 4.0 on logistics management. Recently, Ghadimi et al. (2019) evaluated suppliers' performance with regard to Industry 4.0 criteria. They used a multi-agent system technique to integrate the issue of Industry 4.0 with SSS. Kusi-Sarpong et al. (2019a) developed a MCDM model for evaluating suppliers' sustainability performance by considering circular economy and Industry 4.0. The importance degree of each evaluative criterion was calculated using BWM and the suppliers were ranked by applying VIKOR.

As can be observed, the majority of the methods such as AHP, ANP, TOPSIS, and VIKOR compute the relative performance of suppliers. It means that they need a complete data set for all the suppliers. If there is a data set for only one supplier, these methods cannot compute the performance value of that supplier. Indeed, if a new supplier and its data set are added to the current group, the above-mentioned methods have to redo the entire performance calculation. The literature shows that very few studies have applied FIS as a method to calculate suppliers' performance separately, one by one (Liu et al., 2021). In addition, previous studies used AHP or fuzzy AHP for weighting the attributes, but this method is very time-consuming and needs many pairwise comparisons. In contrast, FBWM is less exhaustive and requires fewer pairwise comparisons (Wang et al., 2020). To date, no research has integrated FBWM with two-stage FIS for Industry 4.0 based SSS.

Research gap

With the advent of Industry 4.0 technologies, SSCM processes have redefined (Oks et al. 2018; Kusi-Sarpong et al. 2019a). As the first echelon of a sustainable supply chain, suppliers need to embrace these technologies. Hence, one of the issues recently gained importance is to consider Industry 4.0 in the SSS. The literature reveals that very few studies have been done on Industry 4.0 with regard to the SSCM. Having a suitable set of Industry 4.0 concepts with sustainability criteria is crucial to ensure the effectiveness of the evaluation process. Therefore, the first research gap is the lack of an integration of SSS with Industry 4.0 attributes, and this study contributes a set of conventional sustainability criteria for SSS with Industry 4.0.

In order to determine the importance weights of the criteria, AHP as a MCDM technique has been widely used (Lasi et al. 2014; Hofmann and Rüsch 2017). AHP requires many pairwise comparisons which make the weighting process very time-consuming. It also needs tremendous calculation (Rashidi and Cullinane 2019). In order to cope with this problem, BWM as a new MCDM method has been developed (Oztaysi 2014). This method needs less computational time in comparison to AHP. However, BWM is unable to deal with fuzziness and vagueness (Tian et al. 2018). Therefore, a fuzzy modification of BWM is needed (Rezaei 2016). Moreover, most of the previous methods are unable to evaluate suppliers' performance separately. This is because they compute each supplier's performance in comparison with other suppliers. When there are n suppliers and a new supplier is added to the group, the decision-maker must recalculate all the performance values because the performance values of $n+1$ suppliers are different from those of n suppliers. In order to address this problem, FIS as a method which does not need a full data set for all the suppliers can be very helpful. In FIS, adding or removing a supplier from the list of alternatives does not affect the performance computation process. Motivated by the aforementioned issues, the second objective of this study is to develop a new integrated FBWM based on a two-stage FIS model for the evaluation of SSS with Industry 4.0 concept.

Proposed approach

Here, the integrated approach of this study is explained. Since the theory of triangular fuzzy numbers (TFN) is well-known and many studies are existed, we avoid presenting it in this paper.

Computing crisp values and aggregation method

To change a TFN into a crisp number, the graded mean integration representation (GMIR) (Eq. (1)) is applied:

$$C_{\tilde{D}} = \frac{l + 4m + u}{6} \tag{1}$$

Assume that $\tilde{I}_i = [(I_{il}, I_{im}, I_{iu})]$ is based on the TFN. To calculate the importance degree of i^{th} criterion (Tian et al. 2018), we have:

$$I_{il} = \frac{1}{d}\sum_{k=1}^{d} I_{il}^{k}, I_{im} = \frac{1}{d}\sum_{k=1}^{d} I_{im}^{k}, I_{iu} = \frac{1}{d}\sum_{k=1}^{d} I_{iu}^{k} \tag{2}$$

Table 2 Most relevant studies

Authors	Models/methods	Explanation	Industry
Moheb-Alizadeh and Handfield (2019)	Multi-objective linear programming (MOLP), DEA,and Benders decomposition algorithm	A MOLP-DEA model was developed to determine sustainable suppliers' efficiencies. By applying a Benders decomposition algorithm, the model was solved. Benders decomposition algorithm is a very rare technique which has been applied in the issue of supplier selection	Automotive industry
Dou et al. (2014)	Grey ANP	A grey ANP model was used to assess and select green supplier development programs. Using grey set theory is contribution of the model. The grey ANP model solved the accuracy problem in measuring suppliers' performance	Pivot irrigation equipment industry
Hashemi et al. (2015)	ANP and grey relational analysis (GRA)	The weights of evaluative criteria were computed using ANP. Then, the best green supplier was determined by applying GRA. Integration of ANP and GRA in the automotive supply chain was totally new	Automotive industry
Lo et al. (2018)	BWM, fuzzy TOPSIS, and fuzzy MOLP	The weight of each green criterion was obtained using BWM. Then, by applying fuzzy TOPSIS, the most suitable suppliers were selected. Finally, a fuzzy MOLP model was developed to optimize the order allocation	Electrical industry
Kannan et al. (2013)	Fuzzy AHP, fuzzy TOPSIS, and MOLP	The weight of each criterion was computed by applying fuzzy AHP. Then, the top green suppliers were selected using fuzzy TOPSIS. Finally, a MOLP model was developed to calculate the maximum total value of purchasing and the minimum total cost of purchasing	Automotive industry
Awasthi and Kannan (2016)	Fuzzy nominal group technique (NGT) and VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	The criteria for evaluating green supplier development programs were identified by applying NGT. Then, the best alternative was selected using VIKOR	Automotive industry
Kuo et al. (2015)	DEMATEL	The main carbon management-based criteria for green supplier selection were determined. Then, DEMATEL was used to deal with the importance and causal relationships among the criteria	Electrical industry
Singh et al. (2018)	Fuzzy AHP, fuzzy DEMATEL, and fuzzy TOPSIS	Fuzzy AHP and fuzzy DEMATEL were used to determine the weight of each green attribute. Fuzzy TOPSIS was then applied to rank suppliers	Food industry
Fallahpour et al. (2021)	Fuzzy DEMATEL, fuzzy ANP, and FIS	The relationship of criteria is calculated by fuzzy DEMATEL. Final weights are done by fuzzy ANP. Finally, the performance of each supplier is done by FIS	Textile industry

Table 3 Linguistic variables for criteria evaluation (Guo and Zhao 2017)

Linguistic variable or term	Membership function
Equally important (EI)	(1,1,1)
Weakly important (WI)	(0.667,1,1.5)
Fairly important (FI)	(1.5,2,2.5)
Very important (VI)	(2.5,3,3.5)
Absolutely important (AI)	(3.5,4,4.5)

where we have d experts and $\tilde{I}_i^k = [(I_{il}^k, I_{im}^k, I_{iu}^k)]$ represents the k^{th} expert's idea for the importance degree of i^{th} criterion.

To rewrite Eq. (2) based on the supplier selection, if assume that $\tilde{x}_i = [(x_{il}, x_{im}, x_{iu})]$ is based on the TFN to calculate the performance rating of a supplier with regard to i^{th} criterion, we have:

$$x_{il} = \frac{1}{d}\sum_{k=1}^{d} x_{il}^k, x_{im} = \frac{1}{d}\sum_{k=1}^{d} x_{im}^k, x_{iu} = \frac{1}{d}\sum_{k=1}^{d} x_{iu}^k \tag{3}$$

Proposed FBWM

BWM was developed by Rezaei [88] as a MCDM technique to ease the criteria weighting process. However, this method is unable to handle ambiguity and vagueness. So, Guo and Zhao (2017) introduced FBWM as a fuzzy modification of BWM. They applied TFNs for performing fuzzy comparisons in their model. They developed Table 3 as the linguistic variables for criteria assessment.

There are five steps in applying FBWM (Guo and Zhao 2017), which are described below.

Bullet Step 1: Creating a fuzzy comparison matrix

A fuzzy comparison matrix can be generated as shown in Eq. (4), when there are n evaluative criteria $\{c_1, c_2, \ldots, c_{n-1}, c_n\}$.

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix} \tag{4}$$

where $\tilde{a}_{ij}$ shows the relative fuzzy preference of criterion i over criterion j (as a TFN) and $\tilde{a}_{ij} = 1/\tilde{a}_{ji}$. It should be mentioned that if $i=j$, then $\tilde{a}_{ij} = (1,1,1)$.

Step 2: Specifying the most important and the least important) evaluative criteria

In this step, the best criterion (C_B) and the worst criterion (C_W) are selected based on the decision-maker's opinion.

Step 3: Implementing the fuzzy preference comparisons for C_B

Specifically, Table 3 is used to determine the fuzzy preferences of the best criterion among other criteria. The obtained matrix is labeled as $\tilde{A}_B$.

$$\tilde{A}_B = (\tilde{a}_{B1}, \tilde{a}_{B2}, \ldots, \tilde{a}_{B(n-1)}, \tilde{a}_{Bn}) \tag{5}$$

It should be mentioned that $\tilde{a}_{BB} = (1,1,1)$

Step 4: Implementing the fuzzy preference comparisons for C_W

Likewise, Table 3 is used to determine the fuzzy preferences of all the criteria over the worst criterion. The obtained matrix is labeled as $\tilde{A}_w$.

$$\tilde{A}_W = (\tilde{a}_{1W}, \tilde{a}_{2W}, \ldots, \tilde{a}_{(n-1)W}, \tilde{a}_{nW}) \tag{6}$$

It should be noted that $\tilde{a}_{WW} = (1,1,1)$

Step 5: Computing the optimal fuzzy weights $\left(\tilde{w}_1^*, \tilde{w}_2^*, \ldots, \tilde{w}_{n-1}^*, \tilde{w}_n^*\right)$

Based on the weights given in Eq. (6), we can optimize the fuzzy weights to minimize the deviation as given in Eq. (7):

$$\min \tilde{\varepsilon}$$

$$s.t.\begin{cases} \left|\left(\tilde{w}_B / \tilde{w}_j\right) - \tilde{a}_{Bj}\right| \leq \tilde{\varepsilon} \\ \left|\left(\tilde{w}_j / \tilde{w}_W\right) - \tilde{a}_{jW}\right| \leq \tilde{\varepsilon} \\ \sum_{j=1}^{n} R(\tilde{w}_j) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ l_j^w \geq 0 \\ j = 1,2,\ldots,n \end{cases} \tag{7}$$

So, by solving the mathematical model above, the optimal fuzzy weights $\left(\tilde{w}_1^*, \tilde{w}_2^*, \ldots, \tilde{w}_{n-1}^*, \tilde{w}_n^*\right)$ and $\tilde{\varepsilon}^*$ are obtained. Then, by using GMIR (Eq. (1)), the irrespective crisp values are computed. GMIR is used because of its simplicity and accuracy and its ability to generate a balanced crisp number (Rezaei, 2016; Guo and Zhao, 2017). Moreover, it is very suitable to defuzzify a TFN. Another important issue in FBWM is determining the consistency ratio (CR). In order to calculate CR, Guo and Zhao (2017) indicated that the crisp ε^* value should be divided by the corresponding consistency index (CI) value of $\tilde{a}_{BW}$ (see Table 4). It is noted that CI is the maximum possible ε value. For example, if $\tilde{a}_{BW} =$ (1.5,2,2.5) and ε^*= 0.4121, then CR = 0.4121/5.29 = 0.078.

Table 4 The CI for FBWM (Guo and Zhao 2017)

Linguistic term	EI	WI	FI	VI	AI
$\tilde{a}_{BW}$	(1,1,1)	(0.667,1,1.5)	(1.5,2,2.5)	(2.5,3,3.5)	(3.5,4,4.5)
CI	3.00	3.80	5.29	6.69	8.04

Table 5 Fuzzy rule bases

Second input	First input				
	VP	**P**	**M**	**G**	**VG**
VP	VP	VP	P	P	M
P	VP	P	P	M	M
M	P	P	M	M	G
G	P	M	M	G	G
VG	M	M	G	G	VG

FIS for performance evaluation

FIS is defined by some rules to ease the estimation of an output by the decision-makers. The logic of FIS works using IF–THEN rules. From the literature, there are two famous IF–THEN rules named as Mamdani- and Sugeno-Mamdani-based methods. This study is a Mamdani-based structure. It can be defined as follows: IF x_1 (first input) is O_1 (first linguistic variable) AND x_2 (second input) is O_2 (second linguistic variable) AND x_n(n^{th} input) is O_n (n^{th} linguistic variable) THEN y is D (the output). For more details about the considered structure, refer to Amindoust et al. (2012).

The complexity of FIS is exponentially difficult. If we have C criteria and M membership functions, the number of rules is M^C. To manage this complexity, the expert can define their rules using only two inputs at each (Amindoust et al. 2012). In this research, after meeting with the experts from the textile company in Iran for our proposed SSS, some fuzzy rules have been defined as given in Table 5. In this regard, following five initial membership functions have been applied:

- Very poor (VP) = (1,2,3)
- Poor (P) = (2,3,4)
- Moderate (M) = (3,4,5)
- Good (G) = (4,5,6)
- Very good (VG) = (5,6,7)

To defuzzify the fuzzy numbers generated by above logic, Eq. (1) is applied to find the crisp values. The inputs of the FIS are these crisp values. At each time, two inputs are considered to manage the complexity. Other inputs are not selected and will be considered for the next hierarchical level (Amindoust et al. 2012). This process is repeated until all inputs are considered in the FIS model.

Proposed weighted two-stage FIS

The developed integrated model comprises three phases as presented in Fig. 1. As can be seen, the first phase selects the relevant criteria for Industry 4.0 and sustainability concepts based on literature review and experts' opinions. In the second phase, data regarding the importance degrees of the criteria are collected from the experts (based on Table 3). As there are more than one expert, Eq. (2) is used as the aggregation method. The importance weights of the criteria are then computed using FBWM. In the third phase, the two-by-two rule-based FIS is applied. Particularly, the FIS consists of two stages. In the first stage, data regarding the performance ratings of the suppliers are collected from the experts (based on the initial membership functions defined in the "FIS for performance evaluation" section). By applying Eq. (3), the aggregated values are obtained. Finally, the weighted data are normalized using Eq. (8).

$$\text{NWD} = \frac{\text{WD}}{\text{MPWD}} \times 100 \tag{8}$$

where the final weighted data is detected by NWD, the weighted data for a criterion is WD, and the maximum possible weighted data for a criterion is MPWD. As known, the range of NWD is between 0 and 100. However, the range of initial member ship functions is between 1 and 7 integrally. Therefore, a new set of membership functions is defined as follows:

$$\text{VP} = (0,20,40);\ \text{P} = (20,40,60);\ \text{M} = (40,60,80);\ \text{G} = (60,80,100);\ \text{VG} = (80,100,100).$$

In general, most of the previous models in the area of supplier selection are not able to measure suppliers' performance individually like FAHP, FANP, FTOPSIS, and FDEA. That is, these models heavily need the decision matrix for evaluating suppliers' performance. But, the current model can handle this problem and measures the suppliers' performance one-by-one. This model allows the managers to simulate the suppliers' performance in different conditions. Moreover, the current model ranks the suppliers based on their performance. In addition, the model combines the concept of Industry 4.0 with sustainability.

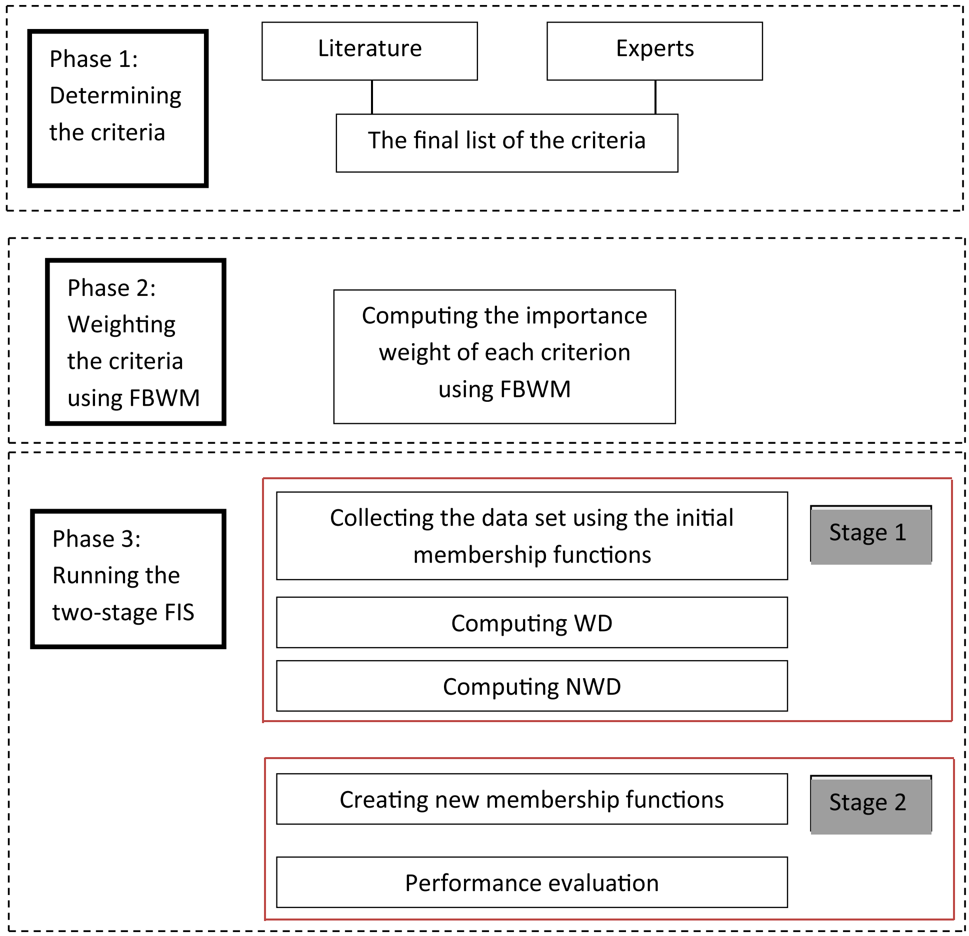

Fig. 1 The integrated model

Case study

The textile companies in Iran have a high impact to the Iranian's GDP.[1] Based on reports from the textile Infomedia's website,[2] Iran's textile market sector exports products to majorly in Afghanistan with $ 245.2 M (in million) USD, and the estimation of export market share to *Afghanistan* is 27.19%. The second market for the textile industry in Iran is the *USA* with $ 245.2 M USD. Exports sector contribution is around 27.19%. *Germany* is another important market for the textile industry in Iran with $ 64.51 M with a market share around 7.15%. As such, Iran imports textile clothing products worldwide from Turkey which is around $ 386.66 M with the import share 24.62%, China which is around $ 342.24 M with the import share 21.79%, and the United Arab Emirates which is around $ 276.47 M with the import share 17.6%. Based on these facts, this industry is very challenging in Iran, and the selection of sustainable suppliers is important. This motivates our attempt to apply our SSS with Industry 4.0 concept for the textile industry in Iran.

To implement the proposed approach, a real case study is conducted in a textile company in Iran, called "company KhR" henceforth. Company KhR is a textile spinning mill with a monthly production of 1.2 tons of yarn per month. Figure 2 shows our company and one of our experts. Cotton yarn, polyester/cotton yarn, and polyester/viscose yarn spun with modern machinery are the final products of the company. This company is one of top three textile companies in Iran. This company aims to improve its partnership with suppliers based on real-time information and sustainability criteria. The KhR company strongly believes that incorporating Industry 4.0 attributes with SSS is one the best ways to improve the competition of this company with other similar ones in Iran.

After consulting with the manager of this company, four experts are employed to collect the data. The first one is a warehouse manager with 5 years of experience. The second one is a procurement manager who works 11 years in this field. The third one is a production manager who works 22 years in this field. The fourth expert is a quality manager who works 19 years in quality control of yarns

[1] Gross domestic product (GDP).

[2] https://www.textileinfomedia.com/textile-industry-in-iran

Fig. 2 Our KhR textile company in Iran

and dyeing materials. We asked these experts to consider their ideas for the linguistic variables in Table 3. Other computations for initial membership functions are done as given in the "FIS for performance evaluation" section.

Criteria selection

The inclusion of Industry 4.0 aspects in SSS is relatively new. Based on the current literature, most of the criteria for assessing sustainable suppliers are the conventional economic, environmental, and social attributes. However, for Industry 4.0 based SSS, it is essential for managers to incorporate criteria from both domains in the evaluation process. In order to obtain the proper criteria, different keywords such as "Sustainable Supplier Selection and Industry 4.0," "Sustainable Supply Chain Management and Industry 4.0," "Green Supply Chain and Industry 4.0," "Green Supplier Selection and Industry 4.0," and "Performance Evaluation and Industry 4.0" were applied in the literature search from Google Scholar, Web of Science, etc.

In total, 18 criteria were solicited from previous studies. These criteria along with their definitions were presented to three experts (two from the academia and one from the industry) for assessment. The first expert is a professor in textile spinning with 19 years of experience in collaboration with the textile industry. The second person is an associate professor in textile technology management with 9 years of experience in this area and SSCM. The third expert is the quality manager of company KhR. No new criterion was added into the list because they indicated that too many criteria would make the respondents confused during evaluation. Table 6 provides the list of Industry 4.0 criteria for the SSS.

Computing the importance weights of the criteria using FBWM

As explained earlier, in FBWM, the best and the worst criteria should be determined. In this research, there are three aspects (economic, environmental and social), and there are several criteria in each aspect. So, the four experts in the case company were asked to determine the most important and the least important aspects and criteria in each aspect, respectively. The results show that the best aspect is economy and the worst aspect is society. Moreover, in the economic aspect, the best criterion is "Price (C12)" and the worst criterion is "Training and awareness on Industry 4.0 (C15)." In the environmental dimension, the best criterion is "Environmental-friendly materials (C21)" and "Green warehouse management (C25)" is the worst criterion. In the social aspect, "Health insurance at work (C31)" is the best and "Organizational culture (C33)" is the worst.

After determining the best and the worst aspects and criteria, the fuzzy preferences or importance degrees of the best-to-others and others-to-worst for the aspects and criteria, respectively, were collected from the four experts. The individual and aggregated data sets for the best-to-others and others-to-worst for the aspects, economic criteria, environmental criteria and social criteria, respectively, are presented in Tables A1 to A8 in Appendix A. The Lingo software 14.0 was used for solving Eq. (6) and obtaining the optimal fuzzy weights. Subsequently, the crisp values of these weights were computed using the GMIR method. Tables 7, 8, 9, and 10 show the optimal weights.

To compute the final weight of each criterion, the weights of each criterion with regard to its corresponding criteria are multiplied. Table 11 presents the final weights of the Industry 4.0 and sustainability criteria.

Table 6 The list of Industry 4.0 criteria for SSS

Aspect	Criterion	Definition
Economic	Quality (C11)	Number of supplied materials rejected by quality control
	Price (C12)	Price of materials considering the quality of materials and other services provided by suppliers
	Flexibility (C13)	Rate of discount given by suppliers
	Service (C14)	Level of service given after delivery of materials
	Training and awareness on Industry 4.0 (C15)	Suppliers should provide training and awareness programs on Industry 4.0 to their employees in order to develop their capabilities
	Smart production and cyber-physical manufacturing systems (C16)	Suppliers should use smart and cyber-physical manufacturing systems to produce their materials and improve their operations
	Information technology (IT) facilities (C17)	Suppliers should have suitable IT facilities, computers and high speed Internet to support Industry 4.0
Environmental	Environmental-friendly materials (C21)	Suppliers should use and produce environmental-friendly materials and avoid non-biodegradable materials
	Collaboration in environmental initiatives using Industry 4.0 technologies (C22)	Suppliers should have environmental collaboration with other companies and parties in a supply chain using Industry 4.0 technologies
	Air emissions (C23)	Quantity control and reduction of hazardous air emissions
	Wastewater (C24)	Quantity control and treatment of wastewater
	Green warehouse management (C25)	Proper warehouse management to reduce energy consumption and environmental impact
	Readiness to apply Industry 4.0 in green initiatives (C26)	Readiness of suppliers to apply Industry 4.0 in initiatives to green the environment
	Research & development (R&D) in environmental issues using Industry 4.0 technologies (C27)	Suppliers should leverage Industry 4.0 technologies to conduct R&D in environmental issues
	Environmental performance evaluation (C28)	Suppliers should evaluate, monitor and control their environmental performance
Social	Health insurance at work (C31)	Suppliers should ensure that their employees are protected by health insurance
	Work contract (C32)	Suppliers should provide as table work contract to their employees
	Organizational culture (C33)	Suppliers should create a conducive organizational culture for their employees to apply Industry 4.0 and sustainability concepts

Table 7 The weights of the aspects

ε^*	Economic	Environmental	Social	CR
0.397	0.485	0.337	0.178	0.059

Table 8 The weights of the economic criteria

ε^*	C11	C12	C13	C14	C15	C16	C17	CR
0.267	0.112	0.250	0.130	0.099	0.075	0.132	0.202	0.038

Table 9 The weights of the environmental criteria

ε^*	C21	C22	C23	C24	C25	C26	C27	C28	CR
0.266	0.194	0.188	0.114	0.161	0.047	0.151	0.072	0.073	0.040

Evaluating the suppliers using the weighted two-stage FIS

The collected data from KhR Company are given in Table B1 in Appendix B. As given in Eq. (7), WD and NWD

Table 10 The weights of the social criteria

ε^*	C31	C32	C33	CR
0.397	0.485	0.337	0.178	0.059

Table 11 The final weights of the Industry 4.0 and sustainability criteria

Criterion	Global weight	Criterion	Global weight	Criterion	Global weight
C11	0.054	C21	0.065	C31	0.086
C12	0.121	C22	0.063	C32	0.060
C13	0.063	C23	0.038	C33	0.032
C14	0.048	C24	0.054		
C15	0.036	C25	0.016		
C16	0.064	C26	0.051		
C17	0.098	C27	0.024		
		C28	0.025		

are computed by the first stage of the FIS model. These computations are reported in Table 12.

In the second stage of FIS, the NWD values were considered the inputs. Then, the FIS was executed to compute the final performance of each supplier as given in Fig. 3.

The application of FIS can be illustrated by a rule viewer. For example, the rule viewer of the FIS operation associated with C11 and C12 for Supplier 1 (S1) is depicted in Fig. 4. In a rule viewer, each rule is a row of plots, and each input or criterion is a column. The output is shown in the output column. After completing all the FIS operations, S3 (performance = 5.424) is the best, followed by S6 (performance = 5.316), S4 (performance = 4.987), S1 (performance = 4.577), S5 (performance = 4.002), and S2 (performance = 3.916).

Validation of the proposed approach

To validate the proposed approach combining FBWM and FIS, different measurements are done. First, we compute the consistency ratio (CR) to evaluate the FBWM (Rezaei 2016). Second, different defuzzification methods including largest of maximum (LOM), smallest of maximum (SOM), mean of maximum (MOM), bisector of area (BOA), and the center of area (COA), to evaluate the FIS used (Amindoust et al. 2012; Amindoust and Saghafinia 2017). Finally, the FBWM is compared to FAHP.

Evaluation of CR

A lower value for CR around zero is highly preferable and shows a high consistency (Guo & Zhao, 2017). The comparison of our criteria based on the CR is 0.059. Based on the economic criteria, the value of CR is 0.038. Based on the environmental criteria, the value of CR is 0.040. Based on the social criteria, the value of CR is 0.059. These values show that our hybrid methodology is highly efficient as these CR values are close to the zero. Therefore, the final weights are reliable and robust.

Defuzzification models

Here, some sensitivity analyses are done by defuzzification methods. Such methods are useful to assess the accuracy and robustness of our FIS-based model. The methods including LOM, SOM, MOM, BOA, and COA are analyzed. Table 13 shows the rankings of the suppliers, and S3 is the best supplier. This supplier is efficient based on the Industry 4.0 and sustainability criteria.

Comparing FBWM with FAHP

FBWM was compared with FAHP as the latter is a more common and basic MCDM method. In addition, both of them require pairwise comparison data. However, FBWM is very different from FAHP because in FBWM, only the pairwise comparison data related to the best and worst criteria are needed. In contrast, FAHP requires the pairwise comparison data for all the criteria. Additional data were collected from the four experts in the case company and FAHP was applied to determine the weights of the criteria. The FAHP results reveal that the economic aspect (weight = 0.556) is the most significant, followed by the environmental (0.308) and social (0.136) aspects. Table 14 shows the global weight of each criterion obtained by FAHP. As can be seen, "Price (C12)" is the most important criterion. It is followed by "IT facilities (C17)," "Environmental-friendly materials (C21)," "Health insurance at work (C31)," and "Flexibility (C13)." On the other hand, "Green warehouse management (C25)" is the least important criterion with the lowest global weight. Generally, the results from FAHP are somewhat consistent with those from FBWM, thus substantiating the validity of FBWM. As described earlier, the advantage of FBWM is

Table 12 WD and NWD of the suppliers with respect to the Industry 4.0 and sustainability criteria

	C11	C12	C13	C14	C15	C16	C17	C21	C22	C23	C24	C25	C26	C27	C28	C31	C32	C33
S1	4.500	4.750	3.500	5.000	2.750	5.750	5.000	4.500	3.500	3.000	5.750	5.000	2.500	2.500	2.500	3.500	5.500	3.000
WD	0.243	0.575	0.221	0.240	0.099	0.368	0.490	0.293	0.221	0.114	0.311	0.080	0.128	0.060	0.063	0.301	0.330	0.096
NWD	75.000	79.201	58.466	83.333	45.833	95.833	83.333	75.128	58.466	50.000	95.988	83.333	41.830	41.667	42.000	58.333	91.667	50.000
S2	3.500	3.500	2.500	2.500	3.000	2.750	3.500	3.000	3.500	2.000	2.750	2.250	3.500	3.500	3.000	3.000	2.500	3.500
WD	0.189	0.424	0.158	0.120	0.108	0.176	0.343	0.195	0.221	0.076	0.149	0.036	0.179	0.084	0.075	0.258	0.150	0.112
NWD	58.333	58.402	41.799	41.667	50.000	45.833	58.333	50.000	58.466	33.333	45.988	37.500	58.497	58.333	50.000	50.000	41.667	58.333
S3	5.750	5.000	4.500	4.750	5.000	4.500	5.750	5.500	5.000	5.750	5.000	5.000	6.000	5.000	4.500	5.750	5.500	5.000
WD	0.311	0.605	0.284	0.228	0.180	0.288	0.564	0.358	0.315	0.219	0.270	0.080	0.306	0.120	0.113	0.495	0.330	0.160
NWD	95.988	83.333	75.132	79.167	83.333	75.000	95.918	91.795	83.333	96.053	83.333	83.333	100.000	83.333	75.333	95.930	91.667	83.333
S4	5.000	3.500	2.500	3.500	3.000	5.750	2.750	5.750	4.500	3.500	3.000	5.750	2.750	5.000	4.500	2.500	3.500	3.000
WD	0.270	0.424	0.158	0.168	0.108	0.368	0.270	0.374	0.284	0.133	0.162	0.092	0.141	0.120	0.113	0.215	0.210	0.096
NWD	83.333	58.402	41.799	58.333	50.000	95.833	45.918	95.897	75.132	58.333	50.000	95.833	46.078	83.333	75.333	41.667	58.333	50.000
S5	5.750	5.000	4.500	5.000	2.500	2.500	3.500	3.000	2.750	5.000	4.500	3.500	3.000	5.000	2.500	4.500	5.000	2.500
WD	0.311	0.605	0.284	0.240	0.090	0.160	0.343	0.195	0.174	0.190	0.243	0.056	0.153	0.120	0.063	0.387	0.300	0.080
NWD	95.988	83.333	75.132	83.333	41.667	41.667	58.333	50.000	46.032	83.333	75.000	58.333	50.000	83.333	42.000	75.000	83.333	41.667
S6	3.500	5.750	5.00	5.750	3.500	4.750	5.750	4.500	2.500	4.500	5.500	5.750	3.500	5.750	4.500	4.750	5.750	4.500
WD	0.189	0.696	0.315	0.276	0.126	0.304	0.564	0.293	0.158	0.171	0.297	0.092	0.179	0.138	0.113	0.409	0.345	0.144
NWD	58.333	95.868	83.333	95.833	58.333	79.167	95.918	75.128	41.799	75.000	91.667	95.833	58.497	95.833	75.333	79.264	95.833	75.000
MPWD	$0.054 \times 6 = 0.324$	0.726	0.378	0.288	0.216	0.384	0.588	0.390	0.378	0.228	0.324	0.096	0.306	0.144	0.150	0.516	0.360	0.192

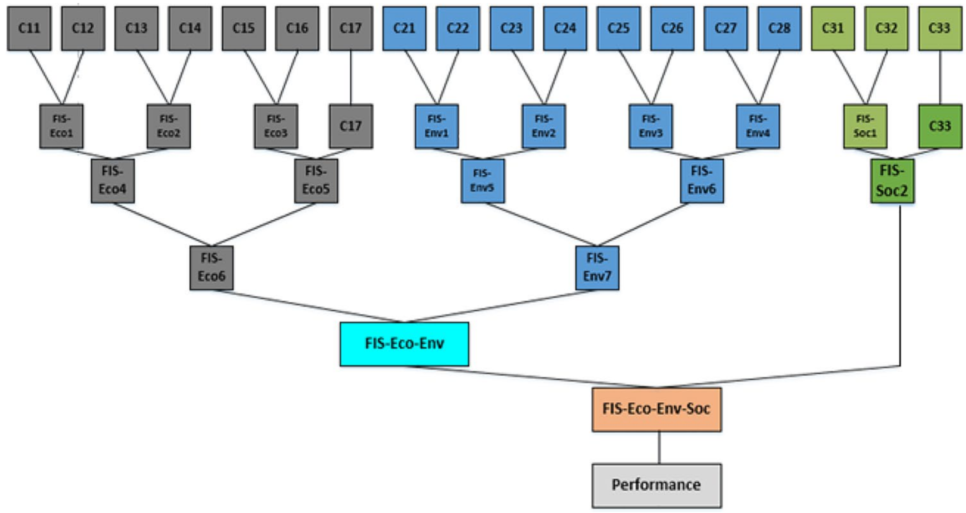

Fig. 3 Two-stage FIS for SSS

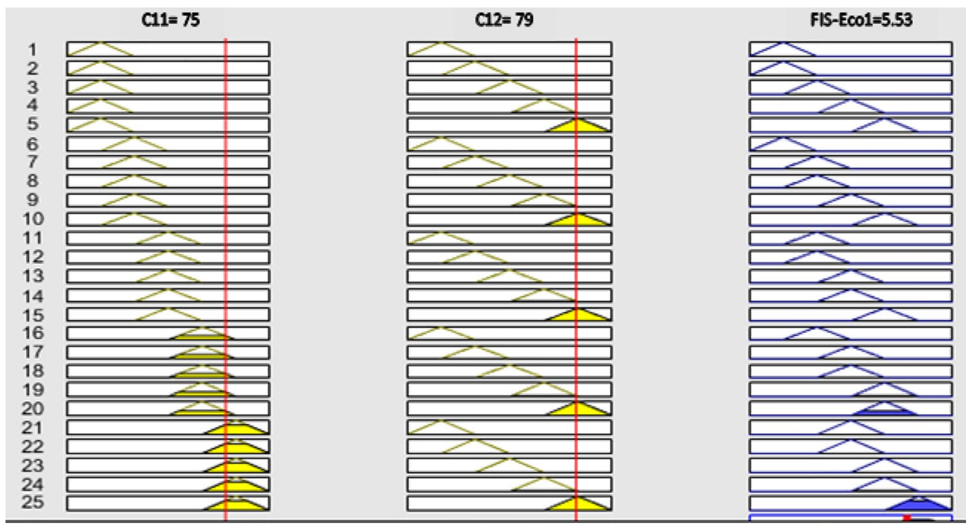

Fig. 4 Rule viewer of the FIS operation related to criteria C11 and C12 for the first supplier

Table 13 Ranking of the suppliers

Supplier	Defuzzification methods				
	COA	BOA	MOM	SOM	LOM
S1	4.577	4.997	4.208	3.668	4.072
Ranking	4	4	4	4	4
S2	3.916	4.037	3.779	3.337	3.925
Ranking	6	6	6	5	5
S3	**5.424**	**5.611**	**5.072**	**4.899**	**5.817**
Ranking	**1**	**1**	**1**	**1**	**1**
S4	4.987	5.009	4.487	3.797	4.287
Ranking	3	3	3	3	3
S5	4.002	4.807	4.007	2.838	3.771
Ranking	5	5	5	6	6
S6	5.316	5.041	4.935	4.299	5.462
Ranking	2	2	2	2	2

that it is more efficient and less time-consuming and requires fewer number of pairwise comparisons than FAHP.

Findings and discussion

Determining the most appropriate supplier among a number of alternatives with respect to multiple attributes is a complicated process (Fallahpour et al. 2017), especially when collecting exact data is not easy. Developing a decision support model in a fuzzy environment helps to address this issue. In this research, a new integrated model consisting of FBWM and two-stage FIS was developed for SSS using Industry 4.0 based sustainability criteria. As shown in Fig. 1, the main phases are collecting the suitable criteria, applying the FBWM, and using the two-stage FIS. A textile spinning

Table 14 The final weights of the criteria obtained by FAHP

Criterion	Global weight	Criterion	Global weight	Criterion	Global weight
C11	0.065	C21	0.091	C31	0.078
C12	0.182	C22	0.037	C32	0.035
C13	0.074	C23	0.027	C33	0.022
C14	0.045	C24	0.026		
C15	0.028	C25	0.015		
C16	0.065	C26	0.030		
C17	0.101	C27	0.050		
		C28	0.034		

company was used as a case study to demonstrate the model, where data were collected from four decision-makers (managers) to assess and rank six suppliers.

The results of FBWM confirm that "Price" is the most crucial economic criterion, while "Environmental-friendly materials" is the most important environmental criterion and "Health insurance at work" is the most important social attribute, if the managers focused on "Flexibility" (with the final weight of 0.063) rather than "Quality" (with the final weight of 0.054). Moreover, "IT of facilities is another crucial attribute" opinions because it is the backbone that supports Industry 4.0. The environmental criteria represented by "R&D in environmental issues using Industry 4.0 technologies" and "Environmental performance evaluation" have almost similar importance. In terms of the social criteria, "Organizational culture" has a lower priority probably because it is an intangible issue which can be dealt with later after the tangible issues ("Health insurance at work" and "Work contract") have been addressed.

After running the two-stage FIS, the results indicate that S3 is the best supplier, followed by S6 and S4. The worst supplier is S2. In addition, three different approaches were applied to demonstrate the robustness and validity of the developed model. The first technique was checking the CR values. The results show that the CR values for all the comparisons are close to zero, which imply a good level of consistency. We applied several defuzzification methods, and among them, S3 was the best supplier. The third technique was comparing the results of FBWM and FAHP. Both methods show that "Price" is the most important criterion.

Managerial implications

This study creates several implications for selecting sustainable suppliers in the Industry 4.0 era. These implications can be elaborated from two perspectives: (i) integration of Industry 4.0 attributes with sustainability criteria for SSS and (ii) development of anew hybridized FBWM with the two-stage FIS model. This research has generated a suitable list of Industry 4.0 based sustainability criteria for SSS. Specifically, 18 criteria were determined, and they were grouped into three aspects (economic, environmental, and social). These criteria are better acquainted with the concepts of Industry 4.0 and sustainability for SSS. The global weights obtained for the criteria can also serve as a pointer for managers to set their priorities in Industry 4.0 based SSS. In addition, an effective integrated model has been developed to evaluate suppliers with respect to the determined criteria. With an implementation of our integrated approach, Industry 4.0 criteria are capable based on the economically, environmentally, and socially sustainable.

Based on the obtained results, managers can see that "Price" is most important criteria (the weight is 0.121). The findings show that the "Flexibility" criterion is important than "Quality" criterion in our results. It means the weaker suppliers should improve their flexibility to increase their performance. They can increase their flexibility in different issues such as price of the raw material and time of supplying the material. Based on the weighting results, it is seen that the company pays more attention to economic aspect than other aspects. After applying the two-stage FIS, supplier 3 with the maximum performance value (S3 = 5.424) was selected as the best supplier. By checking the results, it can be understood that S1 (performance value = 4.577), S5 (performance value = 4.002), and S2 (performance value = 3.916) are the weakest suppliers. As stated before, these suppliers need to have more concentration on those criteria which have more importance degree.

Theoretical implications

The emergence of Industry 4.0 affects the operations and management of a sustainable supply chain. This study has enriched the literature by linking Industry 4.0 to SSCM. Particularly, it has enhanced the SSS area by considering Industry 4.0 attributes together with sustainability criteria. The set of criteria generated from this study can act as a realistic checklist for researchers to study and investigate the important attributes for Industry 4.0 based SSS. Researchers can also use the criteria to build new models that will further expand the domain. In addition, the development of the integrated FBWM with the two-stage FIS model is absolutely new in the area of Industry 4.0 criteria for the SSS. The developed model uses FBWM to cope with the problem of exhaustive pairwise comparisons in a fuzzy environment and utilizes two-stage FIS as an expert system to assess suppliers separately, rather than relatively. Both FBWM and FIS can handle fuzziness, vagueness, and uncertainty in the assessment process.

Conclusions and future works

Academically, there is a lack of studies considering the Industry 4.0 in the field of SSCM. Particularly, studies that have combined Industry 4.0 attributes with sustainability criteria for SSS are scarce. Most of the previous evaluation models for SSS only provide the relative performance of suppliers. Hence, this research has developed a hybridized FBWM with the two-stage FIS model to evaluate the suppliers using Industry 4.0 and sustainability criteria. The importance weights of the criteria were determined via FBWM, and the performance of each supplier was computed individually via two-stage FIS. In essence, the developed model enables decision-makers to assess suppliers separately and select the best one in a fuzzy environment.

Although this study is among the first studies contributing the SSS with Industry 4.0, there are some limitations which can be addressed in our future works. First, shifting our fuzzy method with the robust optimization is a good suggestion to analyze the uncertainty. Second, implementation of our FBWM with the two-stage FIS method in healthcare informatics or other practical decision-making issues is another alternative for the future work. At last but not least, using recent and state of the art metaheuristics like the lion-inspired optimizer (Yazdani and Jolai, 2016), social engineering optimizer (Fathollahi-Fard et al., 2018), and red deer algorithm (Fathollahi-Fard et al., 2020a, 2020b, 2020c) for optimization of selected suppliers to allocate the orders is a continuation of this paper.

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K. Y. Wong: Original draft; project administration.

S. Rajoo: Original draft; project administration.

A. M. Fathollahi-Fard: Conceptualization; investigation; supervision; review and editing.

J. Antucheviciene: Review and editing.

S. Nayeri: Review and editing.

Availability of data and materials The authors declare that the data are available in the appendix.

Declarations

Ethics approval Not applicable.

Consent to participate The authors declare that they agree to participate in this journal.

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